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(54) **ELECTRICALLY POWERED SUSPENSION SYSTEM**

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B60G 17/016 (2006.01)
B60G 17/018 (2006.01)

(52) **U.S. Cl.**

CPC ***B60G 17/0157*** (2013.01); ***B60G 17/0164*** (2013.01); ***B60G 17/018*** (2013.01);
(Continued)

(58) **Field of Classification Search**

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(Continued)

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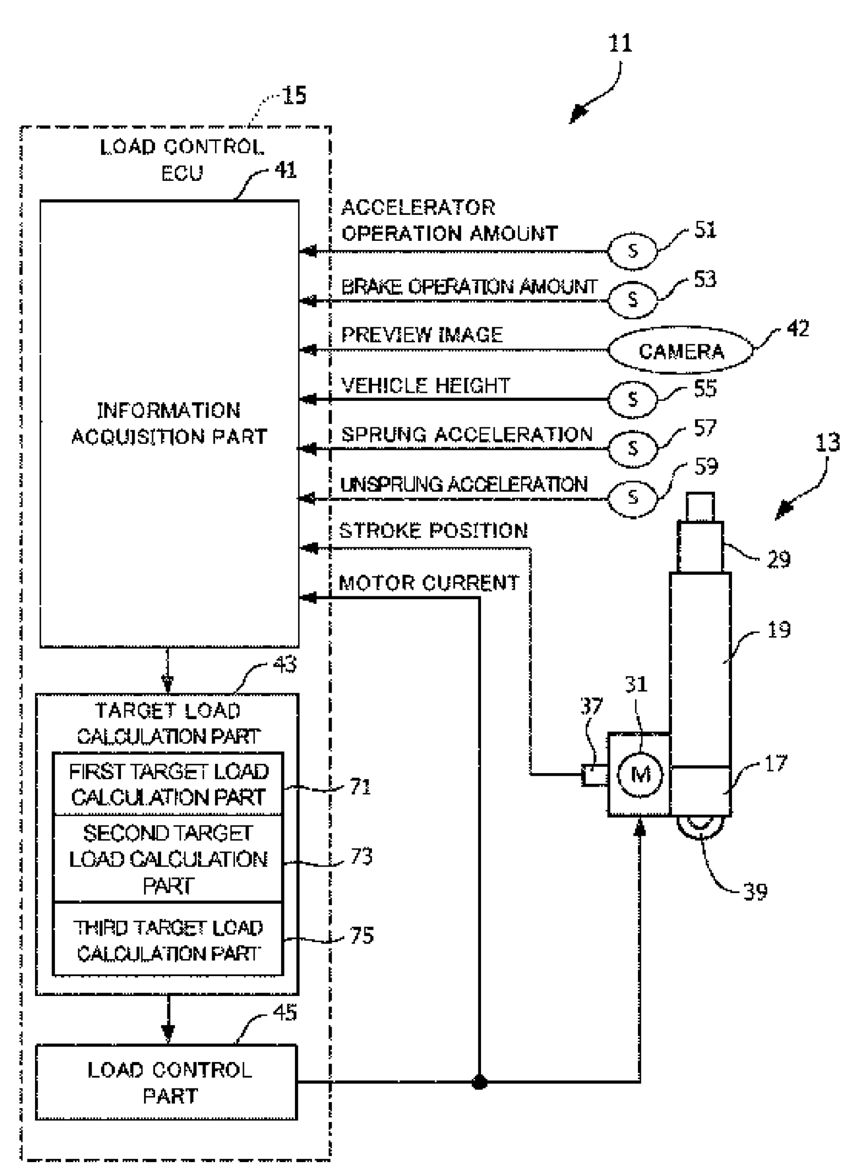
(57) **ABSTRACT**

An electrically powered suspension system includes: an actuator that is provided between a vehicle body and a wheel of a vehicle and generates a load for damping vibration of the vehicle body; an information acquisition part that acquires information on a sprung state amount and a road surface state; a target load calculation part that calculates a first target load related to skyhook control based on the sprung state amount and calculates a second target load related to preview control based on the road surface state; and a load control part. The target load calculation part calculates a third target load related to pitch generation control based on a target pitch angle and calculates a combined target load into which the first target load, second target load, and third target load have been combined. The load control part performs load control of the actuator using the combined target load.

3 Claims, 7 Drawing Sheets



(52) **U.S. Cl.**
CPC *B60G 2202/422* (2013.01); *B60G 2400/0512* (2013.01); *B60G 2400/0522* (2013.01); *B60G 2400/106* (2013.01); *B60G 2400/206* (2013.01); *B60G 2400/60* (2013.01); *B60G 2600/12* (2013.01)

(58) **Field of Classification Search**
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USPC 701/37, 38
See application file for complete search history.

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WO WO-2013111500 A1 * 8/2013 .... B60G 17/0165

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FIG. 1

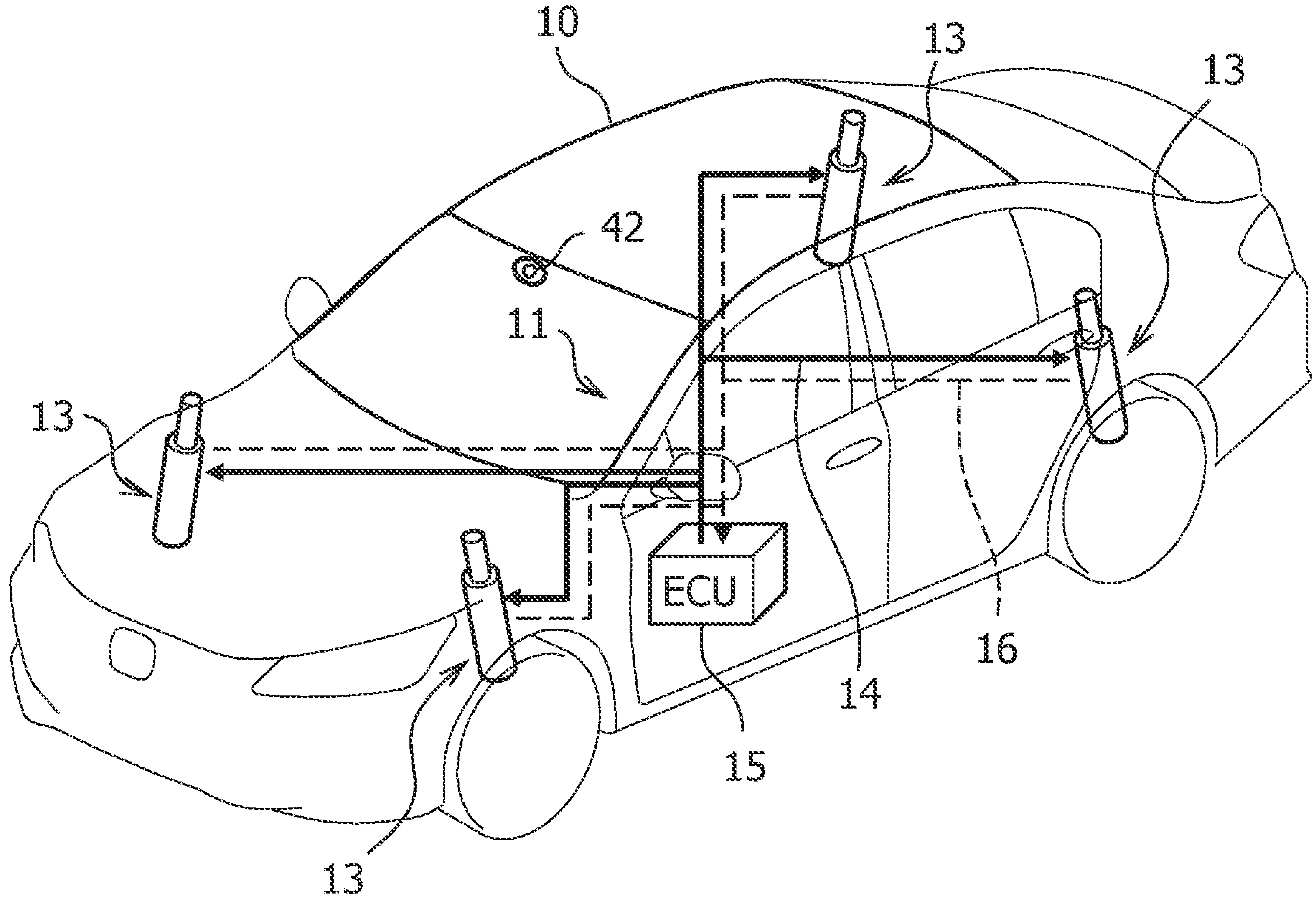
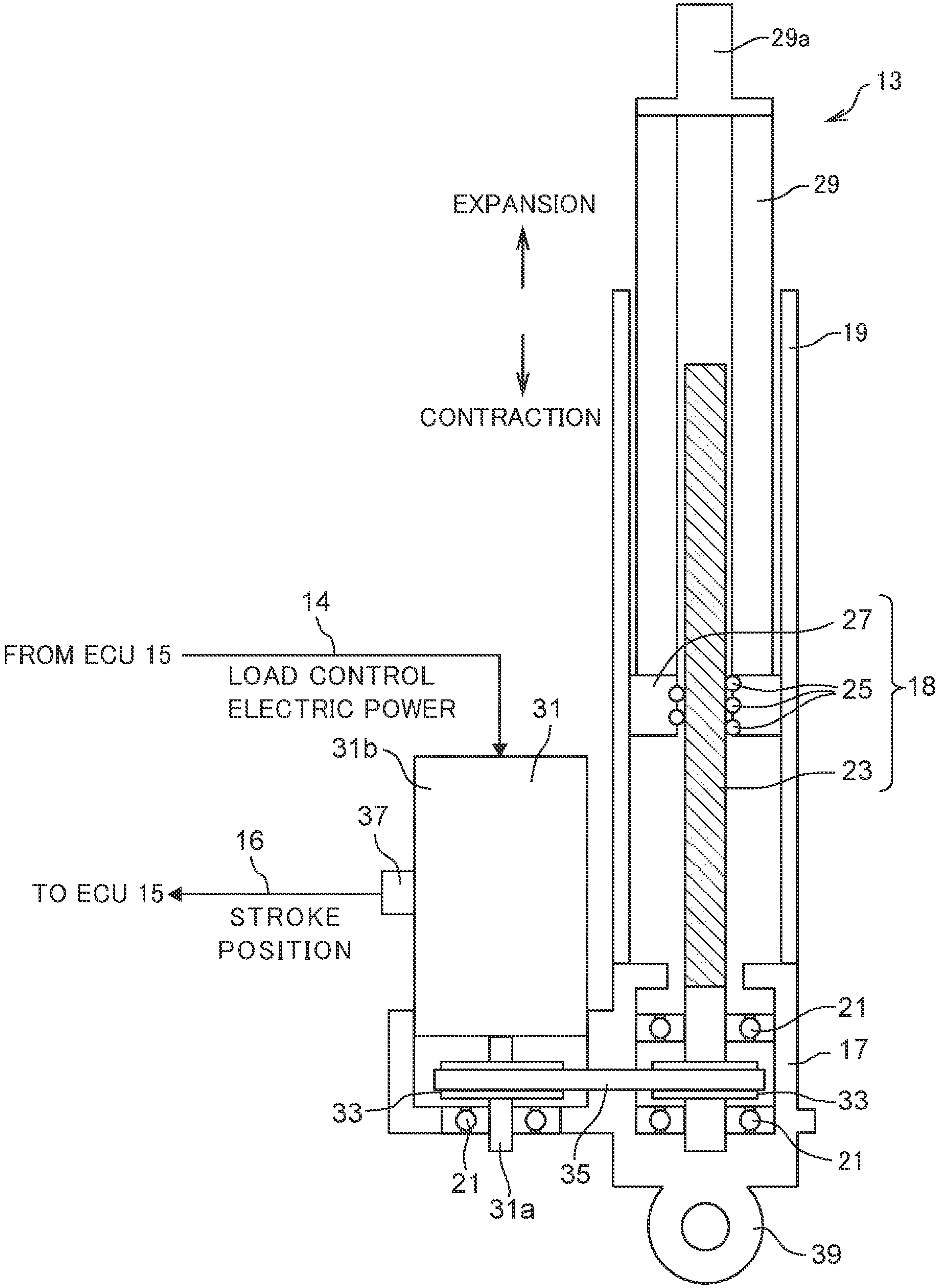


FIG. 2



29a
13
29
EXPANSION
CONTRACTION
19
27
25
18
23
14
FROM ECU 15
LOAD CONTROL
ELECTRIC POWER
31
31b
37
16
TO ECU 15
STROKE
POSITION
21
17
33
33
35
21
21
31a
39

FIG. 3

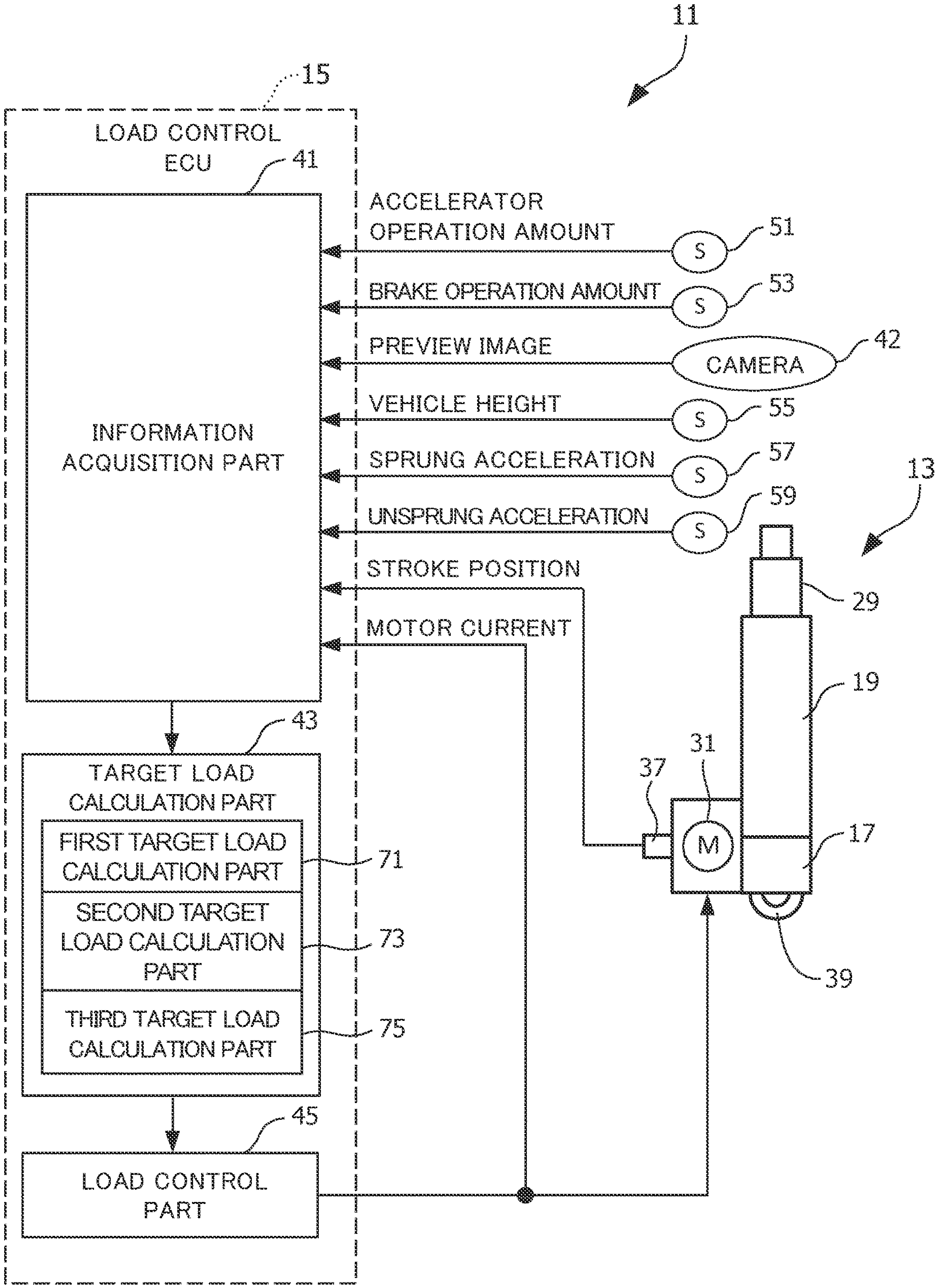

11
15
LOAD CONTROL
ECU
41
INFORMATION
ACQUISITION PART
ACCELERATOR
OPERATION AMOUNT
S
51
BRAKE OPERATION AMOUNT
S
53
PREVIEW IMAGE
CAMERA
42
VEHICLE HEIGHT
S
55
SPRUNG ACCELERATION
S
57
UNSPRUNG ACCELERATION
S
59
STROKE POSITION
MOTOR CURRENT
13
29
19
31
37
M
17
39
43
TARGET LOAD
CALCULATION PART
FIRST TARGET LOAD
CALCULATION PART
71
SECOND TARGET
LOAD CALCULATION
PART
73
THIRD TARGET LOAD
CALCULATION PART
75
45
LOAD CONTROL
PART

FIG. 4

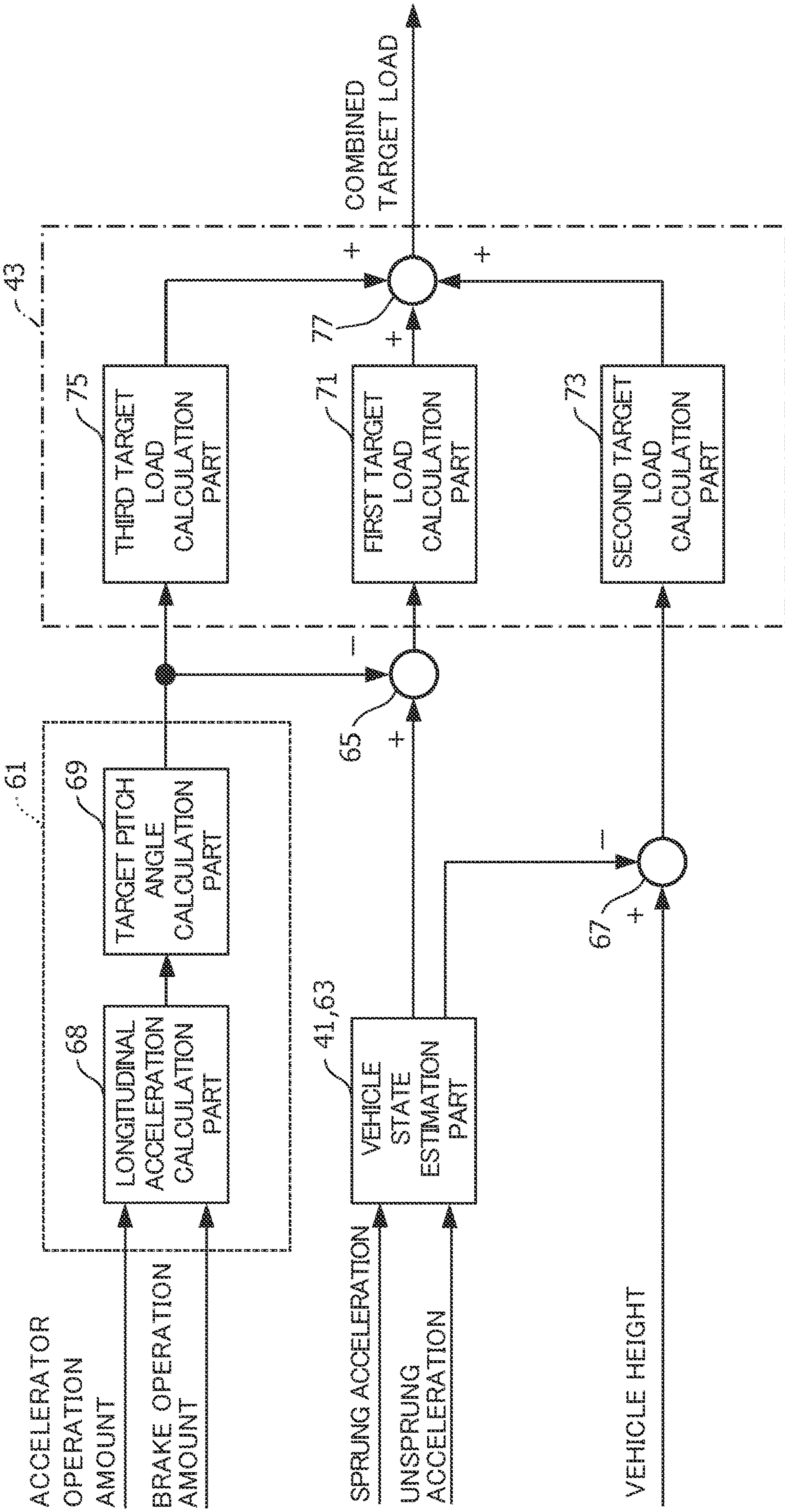

ACCELERATOR OPERATION AMOUNT
BRAKE OPERATION AMOUNT
SPRUNG ACCELERATION
UNSPRUNG ACCELERATION
VEHICLE HEIGHT
61
68
LONGITUDINAL ACCELERATION CALCULATION PART
69
TARGET PITCH ANGLE CALCULATION PART
41, 63
VEHICLE STATE ESTIMATION PART
65
67
43
75
THIRD TARGET LOAD CALCULATION PART
71
FIRST TARGET LOAD CALCULATION PART
73
SECOND TARGET LOAD CALCULATION PART
77
COMBINED TARGET LOAD

FIG. 5A

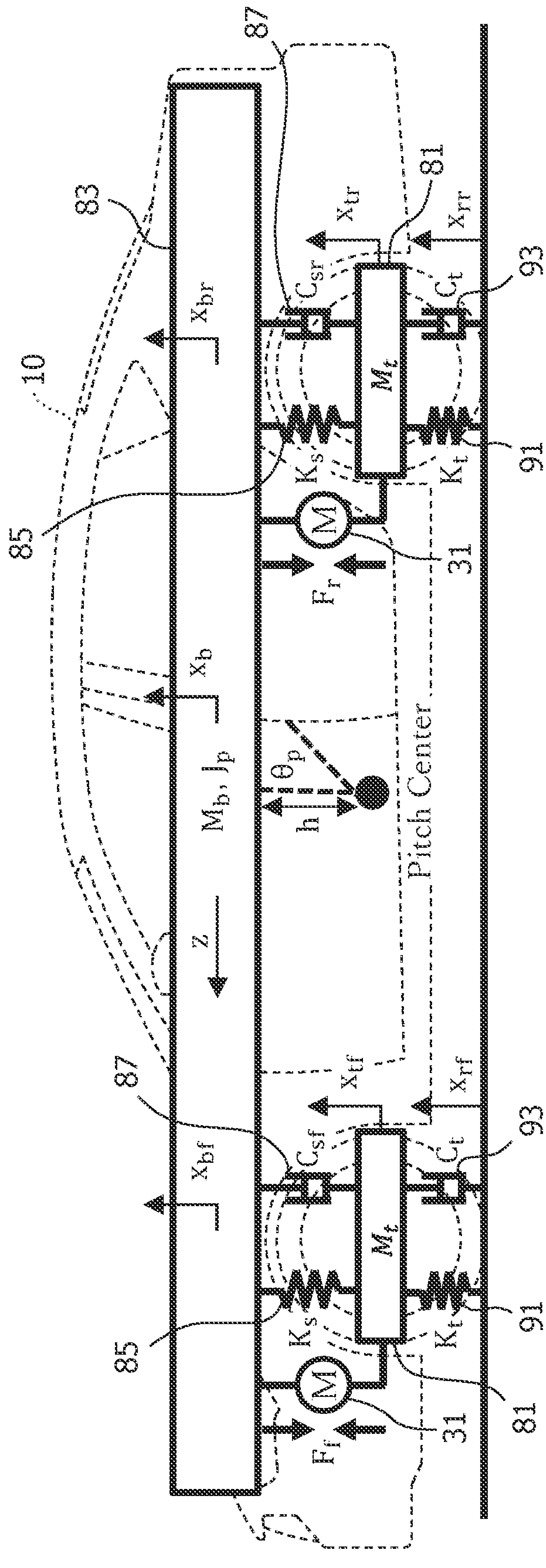


FIG. 5B

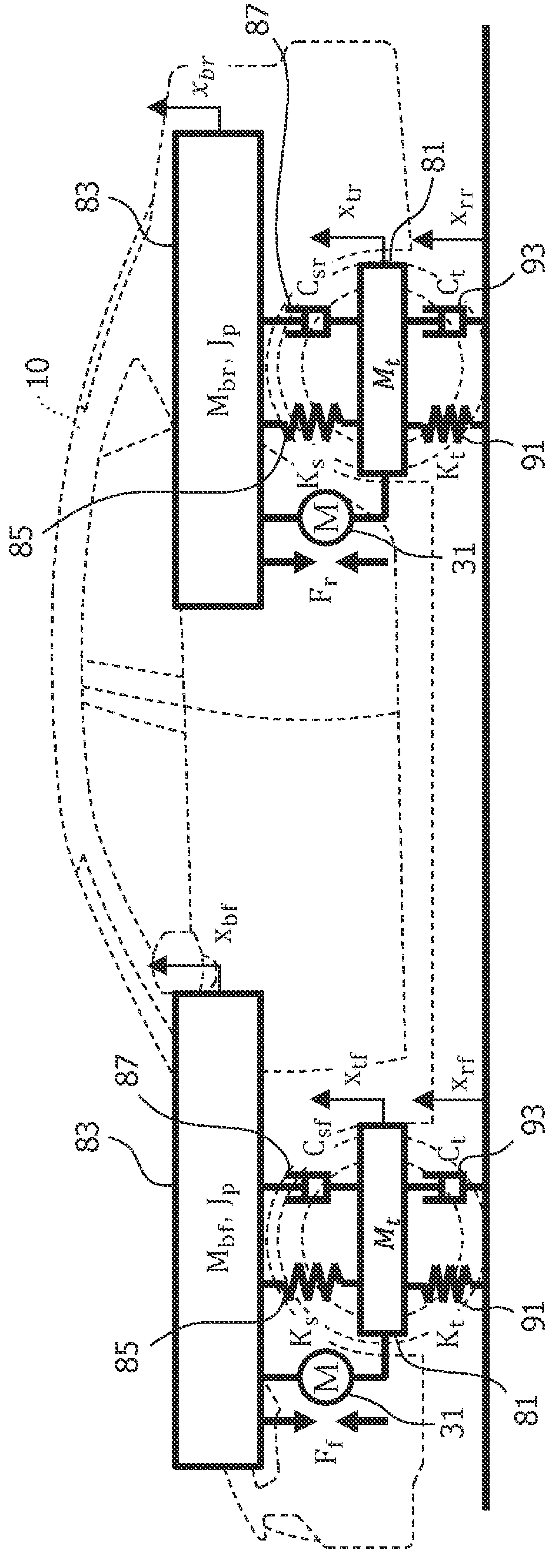
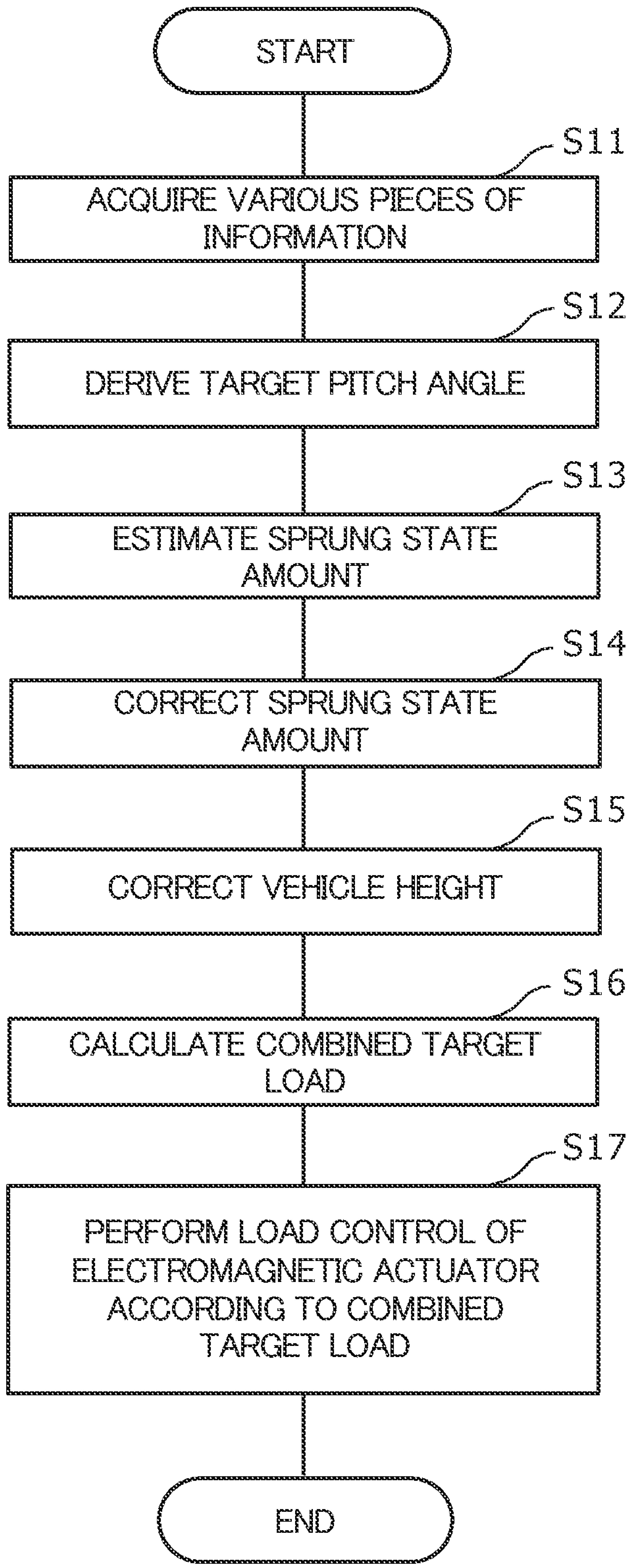

10
83
85
87
81
31
91
93
M_{br}, J_p
M_{bf}, J_p
M_t
K_s
K_t
C_{sr}
C_{sf}
C_t
x_{br}
x_{bf}
x_{tr}
x_{tf}
x_{rr}
x_{rf}
F_r
F_f
M

FIG. 6


START
S11
ACQUIRE VARIOUS PIECES OF INFORMATION
S12
DERIVE TARGET PITCH ANGLE
S13
ESTIMATE SPRUNG STATE AMOUNT
S14
CORRECT SPRUNG STATE AMOUNT
S15
CORRECT VEHICLE HEIGHT
S16
CALCULATE COMBINED TARGET LOAD
S17
PERFORM LOAD CONTROL OF ELECTROMAGNETIC ACTUATOR ACCORDING TO COMBINED TARGET LOAD
END

ELECTRICALLY POWERED SUSPENSION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the foreign priority benefit under Title 35 U.S.C. § 119 of Japanese Patent Application No. 2021-047966, filed on Mar. 22, 2021, in the Japan Patent Office, the disclosure of which is herein incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to an electrically powered suspension system including an actuator that is provided between a vehicle body and a wheel of a vehicle and configured to generate a load for damping vibration of the vehicle body.

2. Description of Related Art

An electrically powered suspension system including an actuator provided between a vehicle body and a wheel of a vehicle and configured to generate a load for damping vibration of the vehicle body is conventionally known. For example, see Japanese Patent Publication No. 2018-134899 (hereinafter referred to as Patent Literature 1).

The electrically powered suspension system described in Patent Literature 1 includes, in a system through which influence of an input of a disturbance is outputted with a delay, a control device that controls a control target that is capable of controlling the output. The control device generates a control instruction that cancels the influence of the disturbance on the basis of: a transfer function from the input of the disturbance to the output of the system; a transfer function from a control instruction to the output, the control instruction being to be issued to the control target controlling the output of the system; and information on the disturbance inputted to the system.

According to the electrically powered suspension system described in Patent Literature 1, the control device operates so as to cancel the vibration of the vehicle body caused by a road surface input, thereby to reduce the vibration of the vehicle body.

Incidentally, in sporty driving a front-wheel drive vehicle, there is a demand for quickly switching the advancing direction of the vehicle by utilizing the tack-in phenomenon (known as a power-off reaction of the vehicle in a turn, which causes the vehicle to head sharply toward the direction of the turn) due to the pitching behavior (nosediving behavior) that is generated in a brake operation of the vehicle.

However, the electrically powered suspension system described in Patent Literature 1 operates such that the control device restrains, regardless of whether sporty driving is being performed, the pitching behavior (nosediving behavior) that normally occurs when braking the vehicle. Then, in sporty driving a front-wheel drive vehicle, it is not possible to quickly switch the advancing direction of the vehicle by utilizing the tack-in phenomenon. Therefore, the sense of unity of human and automobile in sporty driving is decreased. As a result, there is a risk that the driver may feel uncomfortable.

SUMMARY OF INVENTION

In view of the above-described situation, an object of the present invention is to provide an electrically powered suspension system that is capable of producing a good ride quality with a sense of unity of human and automobile even when performing a brake operation in sporty driving.

To achieve the object, an electrically powered suspension system according to a first aspect of the present invention includes: an actuator provided between a vehicle body and a wheel of a vehicle and configured to generate a load for damping vibration of the vehicle body; an information acquisition part configured to acquire information on a sprung state amount of the vehicle and information on a road surface state of a road on which the vehicle is traveling; a target load calculation part configured to calculate a first target load related to skyhook control based on the sprung state amount and to calculate a second target load related to preview control based on the road surface state of the road on which the vehicle is traveling; and a load control part configured to perform load control of the actuator using the calculation results of the target load calculation part. The information acquisition part is further configured to acquire information related to longitudinal acceleration and deceleration of the vehicle. The electrically powered suspension system further includes a target pitch angle derivation part configured to derive a target pitch angle of the vehicle on the basis of the information related to the longitudinal acceleration and the deceleration of the vehicle. The target load calculation part is further configured to calculate a third target load related to pitch generation control based on the target pitch angle derived by the target pitch angle derivation part and to calculate a combined target load into which the first target load, the second target load, and the third target load have been combined. The load control part performs load control of the actuator using the combined target load.

The present invention makes it possible to produce a good ride quality with a sense of unity of human and automobile even when performing a brake operation in sporty driving.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a view illustrating an entire configuration of an electrically powered suspension system according to an embodiment of the present invention.

FIG. **2** is a partial cross-sectional view of an electromagnetic actuator included in the electrically powered suspension system according to the embodiment of the present invention.

FIG. **3** is a block diagram illustrating internal and peripheral parts of a load control ECU (Electronic Control Unit) included in the electrically powered suspension system according to the embodiment of the present invention.

FIG. **4** is a block diagram conceptually illustrating an internal configuration of the load control ECU included in the electrically powered suspension system according to the embodiment of the present invention.

FIG. **5**A is a conceptual diagram for explaining operations of the electrically powered suspension system according to the embodiment of the present invention.

FIG. **5**B is a conceptual diagram for explaining operations of the electrically powered suspension system according to the embodiment of the present invention.

FIG. **6** is a flowchart for explaining operations of the electrically powered suspension system according to the embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

An electrically powered suspension system **11** according to an embodiment of the present invention will be described in detail below with reference to the drawings as appropriate.

Note that, in the drawings referenced hereinafter, basically, members having the same function are denoted by the same reference sign. In this case, as a general rule, a redundant description will be omitted. For convenience of explanation, sizes and shapes of components may be schematically illustrated with deformation or in an exaggerated manner.

[Basic Configuration Common to Electrically Powered Suspension Systems **11** According to Embodiments of the Present Invention]

Firstly, a description will be given of a basic configuration common to the electrically powered suspension systems **11** according to the embodiments of the present invention with reference to FIGS. **1** and **2**.

FIG. **1** is a view illustrating an entire configuration common to the electrically powered suspension systems **11** according to the embodiments of the present invention. FIG. **2** is a partial cross-sectional view of an electromagnetic actuator **13** included in the electrically powered suspension system **11**.

As illustrated in FIG. **1**, the electrically powered suspension system **11** according to the embodiment of the present invention includes a plurality of electromagnetic actuators **13** respectively provided to the wheels of a vehicle **10**, and a load control ECU **15**. The plurality of electromagnetic actuators **13** and the load control ECU **15** are connected to each other with respective electric power supply lines **14** (see the solid lines in FIG. **1**), through which load control electric power is supplied from the load control ECU **15** to the plurality of electromagnetic actuators **13**, and with respective signal lines **16** (see the broken lines in FIG. **1**), through which load control signals of electric motors **31** (see FIG. **2**) are fed from the plurality of electromagnetic actuators **13** to the load control ECU **15**.

In the present embodiment, a total of four electromagnetic actuators **13** are provided respectively to the front wheels (front left wheel and front right wheel) and the rear wheels (rear left wheel and rear right wheel). The electromagnetic actuators **13** provided respectively to the wheels are each separately controlled to damp vibration in conjunction with expansion/contraction operations for the corresponding wheel.

In the embodiment of the present invention, unless otherwise noted, the plurality of electromagnetic actuators **13** each have a common configuration. As such, the configuration of one electromagnetic actuator **13** will be described below as a representative of the plurality of electromagnetic actuators **13**.

As illustrated in FIG. **2**, the electromagnetic actuator **13** includes a base housing **17**, an outer tube **19**, a ball bearing **21**, a ball screw shaft **23**, a plurality of balls **25**, a nut **27**, and an inner tube **29**.

The base housing **17** supports a proximal end side of the ball screw shaft **23** via the ball bearing **21** such that the ball screw shaft **23** is rotatable about its axis. The outer tube **19** is provided on the base housing **17** and accommodates a ball screw mechanism **18** including the ball screw shaft **23**, the plurality of balls **25**, and the nut **27**. The plurality of balls **25** roll along a screw groove of the ball screw shaft **23**. The nut **27** is engaged with the ball screw shaft **23** via the plurality of balls **25** and converts a rotational motion of the ball screw shaft **23** into a linear motion. The inner tube **29**, which is coupled to the nut **27**, moves along the axial directions of the outer tube **19** together with the nut **27**.

In order to transmit a rotational driving force to the ball screw shaft **23**, the electromagnetic actuator **13** includes the electric motor **31**, a pair of pulleys **33**, and a belt member **35**, as illustrated in FIG. **2**. The electric motor **31** is provided on the base housing **17** in parallel to the outer tube **19**. The pulleys **33** are respectively attached to a motor shaft **31***a* of the electric motor **31** and the ball screw shaft **23**. The belt member **35**, which is for transmitting the rotational driving force of the electric motor **31** to the ball screw shaft **23**, is wrapped around the pair of pulleys **33**.

The electric motor **31** is provided with a resolver **37** that detects a rotation angle signal of the electric motor **31**. The rotation angle signal of the electric motor **31**, detected by the resolver **37**, is fed to the load control ECU **15** via the signal line **16**. The rotational driving of the electric motor **31** is controlled in accordance with the load control electric power which is supplied by the load control ECU **15** to the corresponding one of the plurality of electromagnetic actuators **13** via the electric power supply line **14**.

As illustrated in FIG. **2**, the present embodiment employs a layout in which the motor shaft **31***a* of the electric motor **31** and the ball screw shaft **23** are arranged substantially in parallel and connected with each other, thereby shortening the axial dimension of the electromagnetic actuator **13**. Alternatively, another layout may be employed in which, for example, the motor shaft **31***a* of the electric motor **31** and the ball screw shaft **23** are coaxially arranged and connected to each other.

As illustrated in FIG. **2**, the electromagnetic actuator **13** according to this embodiment of the present invention has a connecting portion **39** provided at a lower end of the base housing **17**. The connecting portion **39** is connected and fixed to an unsprung member **81**, non-limiting examples of which unsprung member **81** include a lower arm and a knuckle on the wheel side (see FIG. **5**A). On the other hand, an upper end portion **29***a* of the inner tube **29** is connected and fixed to a sprung member **83**, non-limiting examples of which sprung member **83** include a strut tower portion on the vehicle body side (see FIG. **5**A).

In short, the electromagnetic actuator **13** is arranged in parallel with a spring member (suspension) **85** (see FIG. **5**A) provided between the sprung member (vehicle body) **83** of the vehicle **10** and the unsprung member (e.g., a wheel to which a tire is attached; hereinafter, sometimes generally called "wheel and the like") **81** of the vehicle **10**. The electromagnetic actuator **13** serves as a virtual damper **87** (see FIG. **5**A) that buffers the expansion/contraction force of the spring member (suspension) **85**.

The unsprung members (wheels and the like) **81** respectively provided to right and left wheels are connected with each other via a not-shown stabilizer.

A spring component **91** and a damper component **93** are interposed between the unsprung member (wheel and the like) **81** of the vehicle **10** and the road surface. In short, the tire attached to the wheel of the vehicle **10** functions as the spring component **91** and the damper component **93**.

The electromagnetic actuator **13** configured as described above operates as follows. Specifically, consider a case where, for example, a thrust related to upward vibration is inputted into the connecting portion **39** from the wheel side of the vehicle **10**. In such a case, the inner tube **29** and the nut **27** attempt to descend together with respect to the outer tube **19**, to which the thrust relating to the upward vibration has been applied. In response to this, the ball screw shaft **23** attempts to rotate in a direction to follow the descending of the nut **27**. In this event, the electric motor **31** is caused to generate a rotational driving force in a direction in which the rotational driving force impedes the descending of the nut **27**. This rotational driving force of the electric motor **31** is transmitted to the ball screw shaft **23** via the belt member **35**.

In this manner, the electromagnetic actuator **13** exerts a reaction force (attenuation force) on the ball screw shaft **23** against the thrust related to the upward vibration, thereby to attenuate the vibration being to be transmitted from the wheel side to the vehicle body side.

[Internal Configuration of load control ECU **15**]

Next, a description will be given of internal and peripheral configurations of the load control ECU **15** included in the electrically powered suspension system **11** according to the embodiment of the present invention, with reference to FIG. **3**.

FIG. **3** is a block diagram illustrating internal and peripheral parts of the load control ECU **15** included in the electrically powered suspension system **11** according to the embodiment of the present invention.

[Electrically Powered Suspension System **11** According to Embodiment of the Present Invention]

The load control ECU **15** included in the electrically powered suspension system **11** according to the embodiment of the present invention includes a microcomputer that performs various arithmetic processing operations. The load control ECU **15** performs load control on each of the plurality of electromagnetic actuators **13** on the basis of the rotation angle signal including information on the stroke position of the electric motor **31**, detected by the resolver **37**, a combined target load (details described below), a motor current to be applied to the electric motor **31**, and the like. With this, the load control ECU **15** has a load control function that generates a load for an attenuation operation or an expansion/contraction operation of the electromagnetic actuator **13**.

In order to implement such a load control function, the load control ECU **15** includes an information acquisition part **41**, a target load calculation part **43**, and a load control part **45**, as illustrated in FIG. **3**.

As illustrated in FIG. **3**, the information acquisition part **41** acquires time-series information on each of an accelerator operation amount and a brake operation amount. The information on the accelerator operation amount may be acquired through an accelerator sensor **51** that detects an amount of pressing down the accelerator pedal (not shown) of the vehicle **10**. The information on the brake operation amount may be acquired through a brake sensor **53** that detects an amount of pressing down the brake pedal (not shown) of the vehicle **10**. The information acquisition part **41** may consult, in place of or in addition to the information on the brake operation amount, information on the pressure of brake fluid acting on the brake system. In this case, information on the pressure of brake fluid may be acquired through a fluid pressure sensor that detects the pressure of brake fluid acting on the brake system.

The information acquisition part **41** also acquires, as time-series information on a road surface state of a road which is located in the advancing direction of the vehicle **10** and on which the vehicle **10** is traveling, information on a preview image and information on a vehicle height. The information on the preview image may be acquired through, in addition to a camera **42** provided on the vehicle **10**, external world sensors such as a radar and a LIDAR system. The information on the vehicle height may be acquired, for example, through a vehicle height sensor **55** that detects the vehicle height of the vehicle **10**.

The information acquisition part **41** further acquires time-series information on a sprung acceleration and time-series information on an unsprung acceleration. The time-series information on the sprung acceleration may be acquired on the basis of detection values of a sprung acceleration sensor **57** provided on the sprung member (vehicle body) **83** of the vehicle **10**. The time-series information on the unsprung acceleration may be acquired on the basis of detection values of an unsprung acceleration sensor **59** provided on the unsprung member (wheel and the like) **81** of the vehicle **10**.

The pieces of information on the accelerator operation amount, the brake operation amount, the preview image, the vehicle height, the sprung acceleration, the unsprung acceleration, the stroke position of the electromagnetic actuator **13**, and the motor current for the electric motor **31**, acquired by the information acquisition part **41**, are fed to the target load calculation part **43**.

As illustrated in FIG. **3**, the target load calculation part **43** has a function of figuring out a combined target load, which is a target value for an attenuation operation or expansion/contraction operation of the electromagnetic actuator **13**, by calculation using the various pieces of information acquired by the information acquisition part **41**.

The target load calculation part **43** includes a first target load calculation part **71** configured to calculate a first target load for skyhook control, a second target load calculation part **73** configured to calculate a second target load for preview control, and a third target load calculation part **75** configured to calculate a third target load for pitch generation control. The configurations of the first target load calculation part **71**, the second target load calculation part **73**, and the third target load calculation part **75** will be described in detail later.

The load control part **45** calculates a target current value that can produce the combined target load figured out by the target load calculation part **43**. The load control part **45** then performs drive control on the electric motor **31** included in each of the plurality of electromagnetic actuators **13** so that the motor current for the electric motor **31** will follow the target current value calculated. The plurality of electromagnetic actuators **13** are controlled separately to perform load control with respective electric motors **31**.

[Configuration of Main Part of Load Control ECU **15** Included in Electrically Powered Suspension System **11**]

Next, a description will be given of an internal configuration of the load control ECU **15** included in the electrically powered suspension system **11** according to the embodiment of the present invention, with reference to FIGS. **4**, **5**A, and **5**B as appropriate.

FIG. **4** is a block diagram conceptually illustrating an internal configuration of the load control ECU **15** included in the electrically powered suspension system **11** according to the embodiment of the present invention. FIGS. **5**A and **5**B are each a conceptual diagram for explaining operations of the electrically powered suspension system **11**.

As illustrated in FIG. **4**, the load control ECU **15** included the electrically powered suspension system **11** includes: a target pitch angle derivation part **61**, a vehicle state estimation part **63**, a first subtractor part **65**, a second subtractor part **67**, the first target load calculation part **71**, the second target load calculation part **73**, the third target load calculation part **75**, and a combiner part **77**. The vehicle state estimation part **63** also serves as the information acquisition part **41**. The first target load calculation part **71**, the second target load calculation part **73**, and the third target load calculation part **75** are included in the target load calculation part **43**.

The target pitch angle derivation part **61** includes a longitudinal acceleration calculation part **68** and a target pitch angle calculation part **69**.

The target pitch angle derivation part **61** derives a target pitch angle using an equation of motion of a pitch action (see formula (1)), which equation of motion includes the damping coefficient Cs of the virtual dampers **87** of the electromagnetic actuators **13** provided respectively to the four wheels of the vehicle **10** (see FIG. **5**A). Note that the damping coefficients set to the virtual dampers **87** are assumed to be the same for the sake of convenience.

$$J_p\ddot{\theta}_p + \frac{W_b}{2}\{C_s(\dot{x}_{bf} - \dot{x}_{tf}) + K_s(x_{bf} - x_{tf})\} - \frac{W_b}{2}\{C_s(x_{br} - x_{tr}) + K_s(x_{bf} - x_{tf})\} + M_b\ddot{z}h = 0 \ (\cos\ \theta_p \approx 1) \tag{1}$$

In formula (1), J_p represents the pitch moment of inertia of the sprung member (vehicle body) **83**; M_b represents the mass of the vehicle body **83**; W_b represents the half length of the tread distance of the vehicle **10**; K_s represents the spring constant of the spring member (suspension) **85**, where the suspension spring constants of the four wheels are assumed to have the same value; θ_p represents the pitch angle of the vehicle body **83** ($\ddot{\theta}_p$ represents the pitch angle acceleration of the vehicle body **83**); z represents the longitudinal shift of the vehicle body **83** ($\ddot{z}$ represents the longitudinal acceleration of the vehicle body **83**); h represents the distance from the pitch center to the center of gravity of the vehicle body **83**; x_t (x_{tf}, x_{tr}) represents the vertical shift (unsprung shift) of the unsprung member (wheel and the like) **81**, where x_{tf} represents the vertical shift on the front side and x_{tr} represents the vertical shift of the rear side (hereinafter, the notations with postfixes f and r are used in the same manner); and x_b (x_{bf},x_{br}) represents the vertical shift (vehicle body shift) of the vehicle body **83**.

In FIG. **5**A, M_t represents the mass of wheel and the like **81**; x_r (x_{rf},x_{rr}) represents the road surface height input; K_t represents the spring constant of the unsprung member (tire) **81** (the tires of the four wheels are assumed to have the same spring constant); C_t represents the damping constant of the unsprung member (tire) **81** (the tires of the four wheels are assumed to have a common damping coefficient value); and F_f represents the thrust (load) of the front electromagnetic actuator **13** and F_r represents the thrust (load) of the rear electromagnetic actuator **13**.

Front side vehicle body shift x_{bf}, front side vehicle body speed $\dot{x}_{bf}$, rear side vehicle body shift x_{br}, rear side vehicle body speed $\dot{x}_{br}$ can each be expressed using vehicle body shift x_b, vehicle body speed $\dot{x}_b$, pitch angle θ_p, and pitch angle speed $\dot{\theta}_p$ as formula (2).

$$\begin{aligned} x_{bf} &= x_b + \frac{W_b}{2}\sin\theta_p = x_b + \frac{W_b}{2}\theta_p \\ \dot{x}_{bf} &= \dot{x}_b + \frac{W_b}{2}\dot{\theta}_p \\ x_{bf} &= x_b - \frac{W_b}{2}\sin\theta_p = x_b - \frac{W_b}{2}\theta_p \\ \dot{x}_{bf} &= \dot{x}_b - \frac{W_b}{2}\dot{\theta}_p \end{aligned} \tag{2}$$

By substituting formula (2) to formula (1), the equation of motion describing the pitch action, represented by formula (1), is rewritten into the form represented by the following formula (3).

$$J_p\ddot{\theta}_p + \frac{W_b}{2}\left\{C_s\left(\dot{x}_b + \frac{W_b}{2}\dot{\theta}_p - \dot{x}_{tf}\right) + K_s\left(x_b + \frac{W_b}{2}\theta_p - x_{tf}\right)\right\} - \frac{W_b}{2}\left\{C_s\left(\dot{x}_b - \frac{W_b}{2}\dot{\theta}_p - \dot{x}_{tr}\right) + K_s\left(x_b - \frac{W_b}{2}\theta_p - x_{tr}\right)\right\} + M_b\ddot{z}h = 0 \tag{3}$$

The longitudinal acceleration calculation part **68** calculates the longitudinal acceleration $\ddot{z}$ of the vehicle body on the basis of the time-series information on each of the accelerator operation amount and the brake operation amount of the vehicle **10**, acquired by the information acquisition part **41**. The calculation of the longitudinal acceleration $\ddot{z}$ of the vehicle body may be performed, for example, with reference to the vehicle speed, an inclination angle of the road surface (ascending road, descending road, or flat road), and an engine torque.

The vehicle body longitudinal acceleration $\ddot{z}$ calculated by the longitudinal acceleration calculation part **68** is fed to the target pitch angle calculation part **69**.

The target pitch angle calculation part **69** calculates a target pitch angle θ_p on the basis of the vehicle body longitudinal acceleration $\ddot{z}$ calculated by the longitudinal acceleration calculation part **68**.

Specifically, a Laplace transform is applied to the equation of motion of the pitch action, represented by formula (3).

The resultant equation of motion of the pitch action, to which Laplace transformation has been applied, is as the following formula (4):

$$J_p\Theta_p s^2 + \frac{W_b}{2}\left\{C_s\left(X_b + \frac{W_b}{2}\Theta_p - X_{tf}\right)s + K_s\left(X_b + \frac{W_b}{2}\Theta_p - X_{tf}\right)\right\} - \frac{W_b}{2}\left\{C_s\left(X_b - \frac{W_b}{2}\Theta_p - X_{tr}\right)s + K_s\left(X_b - \frac{W_b}{2}\Theta - X_{tr}\right)\right\} + M_b Zhs^2 = 0 \tag{4}$$

In formula (4), s denotes a Laplace operator.

Next, for the sake of convenience, road surface height input x_r (x_{rf},x_{rr}) is assumed to be zero (i.e., the road surface is assumed to have no irregularities) and the vertical shift x_t (x_{tf},x_{tr}) of the unsprung member (wheel and the like) **81** is assumed to be zero. Substitution of these assumed values into formula (4) yields the following formula (5) representing the target pitch angle θ_p of the vehicle body. Note that the vertical shift x_t is assumed to be zero for the sake of convenience because the equation of motion used herein assumes a situation where no road surface input is present. If an equation of motion assuming a road surface input is used, appropriate non-zero values are to be set as a road surface variation.

$$\Theta_p = \frac{-M_b s^2}{J_b s^2 + \frac{W_b^2}{2}(C_s s + K_s)} Z \tag{5}$$

Formula (5) shows that the target pitch angle θ_p is represented as a function of the longitudinal shift z.

The information on the target pitch angle θ_p of the vehicle body, calculated by the target pitch angle calculation part **69**, is fed to the first subtractor part **65** and the third target load calculation part **75**.

The vehicle state estimation part **63** estimates, for example, as current vehicle state amounts, a sprung speed as first vehicle state amount (sprung state amount) and a time integral of the sprung speed as second vehicle state amount, on the basis of the time-series information on the sprung acceleration and unsprung acceleration acquired by the information acquisition part **41**.

The first vehicle state amount (sprung speed) and the second vehicle state amount (time integral of the sprung speed) estimated by the vehicle state estimation part **63** are respectively fed to the first subtractor part **65** and the second subtractor part **67**.

The first subtractor part **65** subtracts the target pitch angle speed $\dot{\theta}_p$ of the vehicle **10**, calculated by the target pitch angle calculation part **69**, from the current first vehicle state amount (sprung speed) estimated by the vehicle state estimation part **63**. In this way, the first vehicle state amount (sprung speed) is corrected by removing the pitch angle speed component from the current first vehicle state amount (sprung speed). The first subtractor part **65** corresponds to the "sprung state amount correction part" of the present invention.

The first vehicle state amount (sprung speed) having been corrected by the first subtractor part **65** is fed to the first target load calculation part **71**.

The second subtractor part **67** subtracts the current second vehicle state amount (time integral of the sprung speed), estimated by the vehicle state estimation part **63**, from the current vehicle height acquired by the information acquisition part **41**. In this way, the vehicle height is corrected by removing a vehicle height component originating in the variation of the sprung speed from the current vehicle height.

The vehicle height corrected by the second subtractor part **67** is fed to the second target load calculation part **73**.

The first target load calculation part **71** calculates a first target load related to skyhook control, on the basis of the first vehicle state amount (sprung speed) corrected by the first subtractor part **65**. Specifically, for example, the first target load calculation part **71**, using a control rule based on the skyhook theory, multiplies the corrected first vehicle state amount (sprung speed) by a skyhook damping coefficient to calculate the first target load.

The first target load calculated by the first target load calculation part **71** is fed to combiner part **77**.

The second target load calculation part **73** calculates a second target load related to preview control, on the basis of the vehicle height corrected by the second subtractor part **67** (on the basis of an actual height from the road surface). Specifically, for example, the second target load calculation part **73** multiplies, using a control rule based on the skyhook theory, the corrected vehicle height (actual height from the road surface) by a preview control gain to calculate the second target load.

The second target load calculated by the second target load calculation part **73** is fed to combiner part **77**.

The third target load calculation part **75** calculates a third target load (F_f,F_r) on the basis of the information on the target pitch angle θ_p of the vehicle **10** calculated by the target pitch angle calculation part **69**.

Specifically, the third target load (F_f,F_r), related to pitch generation control that causes the calculated target pitch angle θ_p to occur, may be calculated in accordance with the following procedure.

First, the one-wheel model illustrated in FIG. **5**B is assumed as the vehicle model, and an equation of motion of the vehicle body, based on the model, is solved by calculation. The equation of motion of the vehicle body may be represented by the following formula (6). Note that instead of assuming the one-wheel model illustrated in FIG. **5**B as the vehicle model, the thrusts may be directly calculated on the basis of the model illustrated in FIG. **5**A.

$$f_f = M_{bf}\ddot{x}_{bf} + C_s(\dot{x}_{bf} - \dot{x}_{tf}) + K_s(x_{bf} - x_{tf})$$

$$f_r = M_{br}\ddot{x}_{br} + C_s(\dot{x}_{br} - \dot{x}_{tr}) + K_s(x_{br} - x_{tr}) \quad (6)$$

Next, a Laplace transformation is applied to the equation of motion of the vehicle body represented by formula (6). The equation of motion of the vehicle body to which the Laplace transformation is applied is as the following formula (7).

$$F_f = M_{bf}X_{bf}s^2 + C_s(X_{bf} - X_{tf})s + K_s(X_{bf} - X_{tf})$$

$$F_r = M_{br}X_{br}s^2 + C_s(X_{br} - X_{tr})s + K_s(X_{br} - X_{tr}) \quad (7)$$

In formula (7), s denotes a Laplace operator.

Next, for the sake of convenience, road surface height input x_r (x_{rf},x_{rr}) is assumed to be zero (i.e., the road surface is assumed to have no irregularities) and the vertical shift x_t (x_{tf},x_{tr}) of the unsprung member (wheel and the like) **81** is assumed to be zero. These assumed values and formula (2) are substituted into formula (7). Then, formula (7), the equation of motion of the vehicle body to which the Laplace transformation has been applied, is converted into the following formula (8).

$$F_f = \frac{W_b}{2}\{M_{bf}s^2 + C_s s + K_s\}\Theta_p \quad (8)$$

$$F_r = -\frac{W_b}{2}\{M_{br}s^2 + C_s s + K_s\}\Theta_p$$

The third target load calculation part **75** calculates the third target load (F_f,F_r), which relates to pitch generation control for causing the target pitch angle θ_p to occur, in accordance with formula (8).

The third target load (F_f,F_r) calculated by the third target load calculation part **75** is fed to combiner part **77**.

The combiner part **77** combines, by addition: the first target load calculated by the first target load calculation part **71**, the second target load calculated by the second target load calculation part **73**, and the third target load calculated by the third target load calculation part **75**, and outputs the result of combining as a combined target load.

The combined target load combined by the combiner part **77** is fed to the load control part **45**.

[Operation of Electrically Powered Suspension System **11**]

Next, a description will be given of the operations of the electrically powered suspension system **11** according to the embodiment of the present invention with reference to FIG. **6**. FIG. **6** is a flowchart for explaining operations of the electrically powered suspension system **11** according to the embodiment of the present invention.

In Step S**11** illustrated in FIG. **6**, the information acquisition part **41** of the load control ECU **15** acquires pieces of information including information on the accelerator operation amount, the brake operation amount, the preview image, the vehicle height, the sprung acceleration, and the unsprung acceleration, of the vehicle **10**.

In Step S**12**, the target pitch angle derivation part **61** of the load control ECU **15** derives the target pitch angle θ_p of the vehicle **10**.

In detail, the longitudinal acceleration calculation part **68** included in the target pitch angle derivation part **61** calculates the longitudinal acceleration $\ddot{z}$ of the vehicle **10** on the basis of the accelerator operation amount and the brake operation amount of the vehicle **10** acquired by the information acquisition part **41**.

Next, the target pitch angle calculation part **69** included in the target pitch angle derivation part **61** calculates the target pitch angle θ_p of the vehicle **10** on the basis of the longitudinal acceleration $\ddot{z}$ calculated by the longitudinal acceleration calculation part **68**.

In Step S**13**, the vehicle state estimation part **63** included in the load control ECU **15** estimates a current sprung state amount (first vehicle state amount: sprung speed) on the basis of the time-series information on the sprung acceleration and unsprung acceleration acquired by the information acquisition part **41**.

In Step S**14**, the first subtractor part **65** included in the load control ECU **15** subtracts the target pitch angle speed $\dot{\theta}_p$ of the vehicle **10**, calculated by the target pitch angle calculation part **69**, from the current first vehicle state amount (sprung speed), estimated by the vehicle state estimation part **63**. In this way, the first vehicle state amount (sprung speed) is corrected by removing the pitch angle speed component from the current first vehicle state amount (sprung speed).

In Step S**15**, the second subtractor part **67** included in the load control ECU **15** subtracts the current second vehicle state amount (time integral of the sprung speed), estimated by the vehicle state estimation part **63**, from the current vehicle height acquired by the information acquisition part **41**. In this way, the vehicle height is corrected by removing a vehicle height component originating in the variation of the sprung speed from the current vehicle height.

In Step S**16**, the target load calculation part **43** included in the load control ECU **15** calculates the combined target load.

Specifically, the first target load calculation part **71** calculates a first target load related to skyhook control, on the basis of the first vehicle state amount (sprung speed) corrected by the first subtractor part **65**. The first target load calculated by the first target load calculation part **71** is a load to reduce vibration that cannot be reduced by the second target load related to the next-described preview control (e.g., vibration due to a factor other than the road surface input).

The second target load calculation part **73** calculates a second target load related to preview control, on the basis of the vehicle height corrected by the second subtractor part **67** (actual height from the road surface). The second target load calculated by the second target load calculation part **73** is a load to reduce a vibration due to a road surface input.

The third target load calculation part **75** calculates a third target load (F_f,F_r) on the basis of the information on the target pitch angle θ_p of the vehicle **10**, calculated by the target pitch angle calculation part **69**. The third target load calculated by the third target load calculation part **75** is a load to cause the target pitch angle θ_p of the vehicle **10** to occur.

The combiner part **77** combines, by addition: the first target load calculated by the first target load calculation part **71**, the second target load calculated by the second target load calculation part **73**, and the third target load calculated by the third target load calculation part **75**, and outputs the result of combining as a combined target load.

In Step S**17**, the load control part **45** included in the load control ECU **15** performs load control of the electromagnetic actuator **13** according to the combined target load, which is the calculation result out of Step S**16**. After that, the load control ECU **15** completes one cycle of the processes.

[Advantageous Effects of Electrically Powered Suspension System **11** According to Embodiment of Present Invention]

An electrically powered suspension system **11** according to a first aspect includes: an actuator (electromagnetic actuator **13**) provided between a vehicle body and a wheel of a vehicle **10** and configured to generate a load for damping vibration of the vehicle body; an information acquisition part **41** configured to acquire information on a sprung state amount related to a sprung part (vehicle body) of the vehicle **10** and information on a road surface state of a road on which the vehicle **10** is traveling; a target load calculation part **43** configured to calculate a first target load related to skyhook control based on a sprung state amount and to calculate a second target load related to preview control based on the road surface state of the road on which the vehicle **10** is traveling. a load control part **45** configured to perform load control of the electromagnetic actuator **13** using the calculation result of the target load calculation part **43**.

The information acquisition part **41** is further configured to acquire information related to longitudinal acceleration and deceleration of the vehicle **10**. The electrically powered suspension system **11** further includes a target pitch angle derivation part **61** configured to derive a target pitch angle of the vehicle **10** on the basis of the information related to the longitudinal acceleration and the deceleration of the vehicle **10**. As the information related to longitudinal acceleration and deceleration of the vehicle **10**, information on the accelerator operation amount and brake operation amount of the vehicle **10** may be utilized as appropriate.

The target load calculation part **43** is further configured to calculate a third target load related to pitch generation control based on the target pitch angle θ_p derived by the target pitch angle derivation part **61** and to calculate a combined target load into which the first target load, the second target load, and the third target load have been combined. The load control part **45** performs load control of the electromagnetic actuator **13** using the combined target load.

Now, consider a case in which sporty driving is performed on a vehicle **10** in which skyhook control and preview control are implemented. In such a case, a control device operates so as to restrain the pitching behavior (nosediving behavior) that would normally occur when braking the vehicle **10**. Then, when performing a brake operation in a sporty driving situation, the driver cannot utilize the tack-in phenomenon due to the pitching behavior (nosediving behavior) to switch the advancing direction of the vehicle **10** quickly. Therefore, the sense of unity of human and automobile in sporty driving is decreased. As a result, there is a risk that the driver may feel uncomfortable.

In view of this, in the electrically powered suspension system **11** according to the first aspect, the target load calculation part **43** is further configured to calculate a third target load related to pitch generation control based on the target pitch angle θ_p derived by the target pitch angle derivation part **61** and to calculate a combined target load into which the first target load, the second target load, and the third target load have been combined; and the load control part **45** performs load control of the electromagnetic actuator **13** using the combined target load.

With the electrically powered suspension system **11** according to the first aspect, the combined target load is calculated by combining the third target load related to the pitch generation control in addition to the first target load related to the skyhook control and the second target load related to the preview control, and this combined target load is used to perform load control of the electromagnetic actuator **13**. As a result, it is possible to produce a good ride quality with a sense of unity of human and automobile even when performing a brake operation in sporty driving.

Moreover, with the electrically powered suspension system **11** according to the first aspect, as the pitching behavior control of the vehicle **10** is restrained in a situation where a pitching behavior occurs in the vehicle **10** as in the case of performing a brake operation in sporty driving, the power consumption can be reduced by the amount by which the pitching behavior control is restrained. As a result, the effect of protecting the vehicle-mounted battery from heat generation and extending the life of the vehicle-mounted battery can be expected as a secondary effect.

An electrically powered suspension system **11** according to a second aspect is the electrically powered suspension system **11** according to the first aspect, wherein the electrically powered suspension system **11** may further include a sprung state amount correction part (first subtractor part **65**) configured to correct the sprung state amount (sprung speed) by subtracting, from the sprung state amount, a pitch angle speed component based on the target pitch angle θ_p, and the target load calculation part **43** may calculate the first target load related to skyhook control on the basis of the sprung state amount after correction.

Regarding the sprung state amount (sprung speed), the sprung state amount correction part (first subtractor part **65**) of the electrically powered suspension system **11** according to the second aspect performs correction to remove a pitch angle speed component from the current sprung speed by subtracting a pitch angle speed component based on the target pitch angle θ_p from the sprung speed, which is the sprung state amount acquired by the information acquisition part **41**.

In short, as the target pitch angle speed component is removed from the basic data (sprung speed) for obtaining the first target load related to skyhook control, the influence of the target pitch angle θ_p to the skyhook control can be removed.

As the electrically powered suspension system **11** according to the second aspect performs correction to remove the pitch angle component from the current sprung speed by subtracting the pitch angle speed component based on the target pitch angle θ_p from the sprung speed, which is the sprung state amount, it is possible to avoid competition of a skyhook control operation and a pitch generation control operation which originate from the same pitch angle speed component compared to the electrically powered suspension system **11** according to the first aspect. As a result, it is possible to reduce an error in the combined target load to perform high-precision load control.

An electrically powered suspension system **11** according to a third aspect is the electrically powered suspension system **11** according to the first or second aspect, wherein the target pitch angle derivation part **61** (see FIG. **4**) may be configured to derive a target pitch angle θ_p using an equation of motion of a pitch action (see formula (1)), the equation of motion including a damping coefficient Cs of a virtual damper **87** (see FIG. **5**A) provided between the vehicle body (sprung member) and a wheel (unsprung member) of the vehicle **10**, and wherein the damping coefficient Cs of the virtual damper **87** may be set to a value according to a preference of a user regarding the pitching behavior of the vehicle **10**.

According to the electrically powered suspension system **11** according to the third aspect, the target pitch angle derivation part **61** is configured to derive a target pitch angle θ_p using an equation of motion of a pitch action, the equation of motion including a damping coefficient Cs of the virtual damper **87** provided between the vehicle body (sprung member) and a wheel (unsprung member) of the vehicle **10**, and the damping coefficient Cs of the virtual damper **87** is set to a value according to a preference of a user regarding the pitching behavior of the vehicle **10**. As a result, it is possible to produce a good ride quality with a better sense of unity of human and automobile compared to the electrically powered suspension system **11** according to the first or second aspect.

[Other Modifications]

The plurality of embodiments described above represent examples of embodying the present invention. Therefore, the technical scope of the present invention should not be construed to be limited to these embodiments. The present invention can be implemented in various embodiments without departing from the gist or the main scope of the present invention.

For example, the electrically powered suspension systems **11** according to the embodiments of the present invention have been described with an exemplary embodiment in which a total of four electromagnetic actuators **13** are arranged for both the front wheels (front left wheel and front right wheel) and the rear wheels (rear left wheel and rear right wheel). However, the present invention is not limited to this configuration. A total of two electromagnetic actuators **13** may be arranged in either the front wheels or the rear wheels.

In addition, the electrically powered suspension systems **11** according to the embodiments of the present invention have been described such that a load control part **45** performs load control on each of a plurality of electromagnetic actuators **13** separately. Specifically, the load control part **45** is configured to perform load control on each of electromagnetic actuators **13** provided respectively on the four wheels, separately.

Alternatively, the load control part **45** may be configured to perform load control of electromagnetic actuators **13** provided respectively on the four wheels, separately for the front wheels and for the rear wheels, or separately for the right wheels and the left wheels.

The electrically powered suspension systems **11** according to the exemplary embodiments of the present invention have been described with application to a vehicle performing a brake operation in sporty driving. However, the present invention is not limited thereto. The present invention may be applied to a vehicle performing a brake operation in normal driving.

Lastly, although the electrically powered suspension systems **11** according to the exemplary embodiments of the present invention have been described with the electromagnetic actuator **13** having a ball screw type actuator as the drive mechanism, the present invention is not limited thereto.

The drive mechanism of the electromagnetic actuator **13** may be of any type, non-limiting examples of which include the linear motor type, the rack and pinion type, and the rotary type.

What is claimed is:

1. An electrically powered suspension system comprising:

an actuator provided between a vehicle body and a wheel of a vehicle and configured to generate a load for damping vibration of the vehicle body;

an information acquisition part configured to acquire information on a sprung state amount of the vehicle and information on a road surface state of a road on which the vehicle is traveling;

a target load calculation part configured to calculate a first target load related to skyhook control based on the sprung state amount and to calculate a second target load related to preview control based on the road surface state of the road on which the vehicle is traveling; and

a load control part configured to perform load control of the actuator using calculation results of the target load calculation part,

wherein the information acquisition part is further configured to acquire information related to longitudinal acceleration and deceleration of the vehicle,

wherein the electrically powered suspension system further comprises a target pitch angle derivation part configured to derive a target pitch angle of the vehicle on the basis of the information related to the longitudinal acceleration and the deceleration of the vehicle,

wherein the target load calculation part is further configured to calculate a third target load related to pitch generation control based on the target pitch angle derived by the target pitch angle derivation part and to calculate a combined target load into which the first target load, the second target load, and the third target load have been combined,

wherein the load control part performs load control of the actuator using the combined target load,

wherein the sprung state amount is a sprung speed,

wherein the electrically powered suspension system further includes a sprung state amount correction part configured to correct the sprung state amount by subtracting, from the sprung speed, a pitch angle speed component based on the target pitch angle, and

wherein the target load calculation part is configured to calculate the first target load related to skyhook control on the basis of the sprung state amount after correction.

2. An electrically powered suspension system comprising:

an actuator provided between a vehicle body and a wheel of a vehicle and configured to generate a load for damping vibration of the vehicle body;

an information acquisition part configured to acquire information on a sprung state amount of the vehicle and information on a road surface state of a road on which the vehicle is traveling;

a target load calculation part configured to calculate a first target load related to skyhook control based on the sprung state amount and to calculate a second target load related to preview control based on the road surface state of the road on which the vehicle is traveling; and

a load control part configured to perform load control of the actuator using calculation results of the target load calculation part,

wherein the information acquisition part is further configured to acquire information related to longitudinal acceleration and deceleration of the vehicle,

wherein the electrically powered suspension system further comprises a target pitch angle derivation part configured to derive a target pitch angle of the vehicle on the basis of the information related to the longitudinal acceleration and the deceleration of the vehicle,

wherein the target load calculation part is further configured to calculate a third target load related to pitch generation control based on the target pitch angle derived by the target pitch angle derivation part and to calculate a combined target load into which the first target load, the second target load, and the third target load have been combined,

wherein the load control part performs load control of the actuator using the combined target load,

wherein the target pitch angle derivation part is configured to derive the target pitch angle using an equation of motion of a pitch action, the equation of motion including a damping coefficient of a virtual damper provided between the vehicle body and a wheel of the vehicle, and

wherein the damping coefficient of the virtual damper is set to a value according to a preference of a user regarding a pitching behavior of the vehicle.

3. The electrically powered suspension system according to claim **1**,

wherein the target pitch angle derivation part is configured to derive the target pitch angle using an equation of motion of a pitch action, the equation of motion including a damping coefficient of a virtual damper provided between the vehicle body and a wheel of the vehicle, and

wherein the damping coefficient of the virtual damper is set to a value according to a preference of a user regarding a pitching behavior of the vehicle.

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